

Heavy flavor production in pp and AA collisions at the LHC

W.M. Alberico^{a,b}, A. Beraudo^c, A. De Pace^b, M. Monteno^{b,*}, A. Molinari^{a,b}, M. Nardi^b,
F. Prino^b

^a*Dipartimento di Fisica dell'Università di Torino, via P. Giuria 1, I-10125 Torino, Italy*

^b*Istituto Nazionale di Fisica Nucleare, Sezione di Torino, via P. Giuria 1, I-10125 Torino, Italy*

^c*Physics Department, Theory Unit, CERN, CH-1211 Genève 23, Switzerland*

Abstract

A refined version of a multi-step calculation of heavy-flavor observables in pp and AA collisions has been developed, based on pQCD at NLO accuracy followed by parton shower evolution to describe heavy-quark production and on the relativistic Langevin equation to describe their stochastic evolution in the QCD plasma. Then, hadronization is modeled through an implementation of fragmentation functions based on pQCD and constrained by e^+e^- collider data. Results of our calculations can be compared with recent measurements performed at the LHC in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV: nuclear modification factor R_{AA} of the p_T spectra at mid-rapidity of heavy-flavor decay electrons and of exclusively reconstructed open-charm mesons at different centralities, as well as their elliptic-flow $v_2(p_T)$ in semi-central collisions. To test the validity of our setup for such studies, its predictions are also checked against the p_T spectra measured in pp collisions at $\sqrt{s}=7$ TeV and 2.76 TeV.

Keywords: heavy ion collisions, heavy quark energy loss, relativistic Langevin equation

1. Introduction

Heavy-flavor measurements in nucleus–nucleus collisions allow to test theoretical predictions about partonic energy-loss in the hot and ultra-dense strongly-interacting matter that is produced.

Results of the heavy-flavor measurements performed by PHENIX and STAR at the RHIC have shown that the suppression of the heavy-flavor decay electron p_T spectra observed in central Au–Au collisions at $\sqrt{s_{NN}}=200$ GeV is underestimated by model calculations implying for heavy-quarks only in-medium radiative energy losses. Such scenario has been confirmed by the first results delivered after the analysis of data collected in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV by the ALICE experiment at the LHC, where the exclusive reconstruction of open-charm hadrons from their hadronic decays complements the inclusive measurement of electron (and muon) spectra.

Such findings gave boost to calculations considering the role of collisional energy loss for heavy quarks.

2. The POWLANG model

In our framework [1, 2] the heavy-quark propagation in QGP is described through a relativistic Langevin equation, where the stochastic noise term is expressed in terms of two momentum-dependent transport-coefficients representing

*Corresponding author

Email address: monteno@to.infn.it (M. Monteno)

the mean squared transverse/longitudinal momentum-change per unit time of the scattered heavy quark. They are computed through pQCD calculations with resummation of medium effects (in HTL approximation) for soft collisions.

The Langevin simulation tool is embedded in a multi-step setup to calculate heavy-flavor observables in pp and AA collisions: c and b quarks are generated using the POWHEG [3] code, implementing pQCD at NLO accuracy, with CTEQ6M PDFs as input, followed by parton shower evolution performed with the PYTHIA code [4] (this feature was not present in the previous version of our tool [1, 2]. For AA collisions, EPS09 [5] nuclear corrections to PDFs are employed; then, heavy quarks are distributed in the transverse plane according to the nuclear overlap function $T_{AB}(x, y) \equiv T_A(x+b/2, y)T_B(x-b/2, y)$ corresponding to the selected impact parameter b ; a broadening of the heavy-quark p_T -spectra due to an intrinsic- k_T (in pp) and to the Cronin effect (in AA) is also included.

Then, only for AA collisions, an iterative procedure is employed to follow the stochastic evolution of the heavy quarks in the plasma until hadronization: the Langevin update of the heavy-quark momentum and position is performed at each step according to the local 4-velocity and temperature $T(x)$ of the expanding background medium, as provided by relativistic hydrodynamic codes [6, 7].

Heavy quarks are made hadronize by sampling different hadron species from c and b fragmentation fractions extracted from experimental data [8, 9, 10]; this approach neglects, by construction, any possible change in the heavy-flavor hadro-chemistry in AA collisions. Then, hadron momenta are sampled from fragmentation functions (FF) calculated in heavy-quark effective theory (HQET) [11], with a single parameter r defined as $r = (m_H - m_Q)/m_H$. In order to evaluate the systematic uncertainties associated to different FF choices, for charmed hadrons we have tested also the values of the r parameter fitted in the FONLL framework [12] to ALEPH data [9] at the LEP e^+e^- collider (i.e. $r = 0.1$ for $m_c = 1.5$ GeV, while it amounts to $r=0.2$ according its definition in [11]; for bottom fragmentation we tested the functional form proposed by Kartvelishvili et al. [13], whose single parameter α was fitted in the FONLL framework [14] to ALEPH [15] and SLD [16] e^+e^- data (namely $\alpha = 29.1$ for $m_c = 4.75$ GeV).

Finally, each heavy-quark hadron is forced to decay into electrons with PYTHIA [4], using updated tables of branching ratios based on Ref. [17].

For brevity, in the following our setup will be named POWLANG (POWHEG+Langevin).

3. Results

As a test of the validity of our setup to make heavy-quark energy loss studies at the LHC, we have checked the consistency of the charm and bottom hadron spectra obtained from POWHEG (followed by the PYTHIA parton shower and by the heavy-quark fragmentation tools described above) with those measured at the LHC in pp collisions at $\sqrt{s}=7$ TeV. Results of these comparisons are shown in Fig. 1.

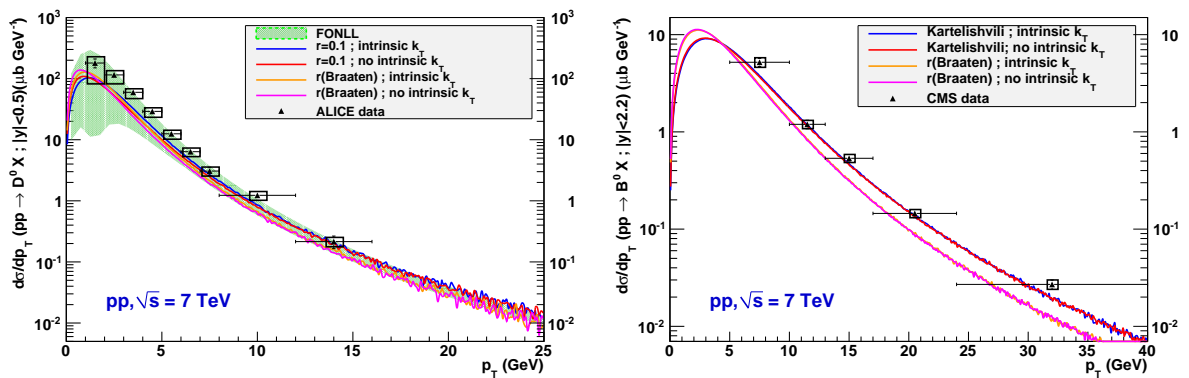


Figure 1. p_T -differential inclusive cross-section in pp collisions at $\sqrt{s} = 7$ TeV for D^0 mesons in $|y| < 0.5$ (left) and for B^0 mesons in $|y| < 2.2$ (right): predictions from POWHEG+PYTHIA under different assumptions on fragmentation functions and on partonic intrinsic- k_T are compared with ALICE [18] and CMS [21] data. For charmed mesons, the theoretical uncertainty band of FONLL [19] predictions is also superimposed.

In the left panel of Fig. 1, the predictions for the D^0 meson inclusive p_T distributions at central rapidity in pp collisions at $\sqrt{s} = 7$ TeV are compared to ALICE data [18] and to the overall uncertainty band of the FONLL [19] prediction, including also systematics from quark mass and μ scale variations. Our results, obtained with different choices of the r parameter of the FF calculated in [11] and with/without intrinsic- k_T , show a small systematic uncertainty from these variations, and are consistent with the FONLL central prediction. The ALICE data points appear located on the upper edge of the FONLL uncertainty band (as it occurred already with D meson data at the Tevatron), and we can conclude that within the large theoretical and experimental systematics they are also in rather good agreement with our calculations. A similar level of agreement with the ALICE data is observed for the p_T distributions of D^+ and D^{*+} mesons, and also for those measured, with low statistics, at $\sqrt{s}=2.76$ TeV [20].

In addition, in the right panel of Fig. 1, our predictions of the B^0 meson inclusive p_T distributions at central rapidity in pp collisions at $\sqrt{s} = 7$ TeV are compared to CMS data from ref. [21]. A good agreement is observed, within respective uncertainties, mostly when Kartelishvili et al. [13] parameterizations are used.

The effects of the Langevin evolution on heavy-quark spectra, as modeled in POWLANG, are displayed in the left panel of Fig. 2, where our results for the nuclear modification factor R_{AA} of D^0 and D^+ mesons produced at mid-rapidity in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV, in the 0 – 20% centrality class, are compared to the ALICE data [22]. The right panel of the same figure shows our predictions for the elliptic-flow v_2 of D^0 and D^+ mesons produced at mid-rapidity in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV in the 30 – 50% centrality class, that can be compared with the preliminary ALICE data shown at this conference in [23], but not yet published.

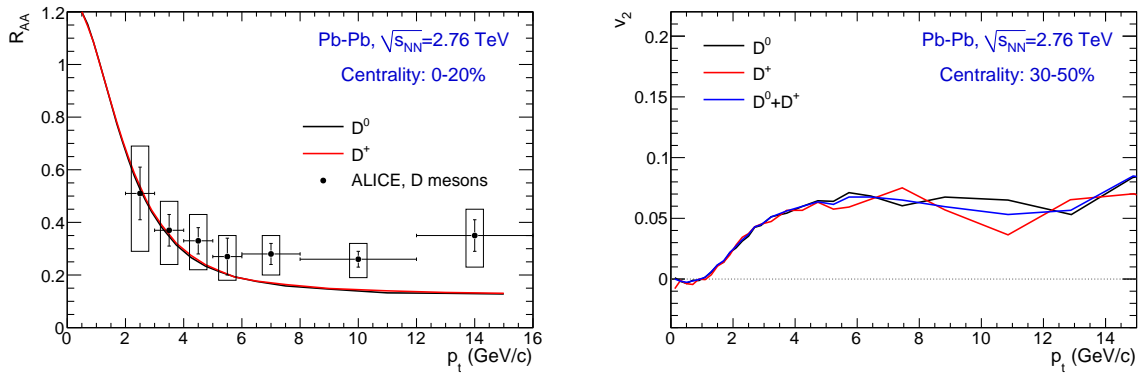


Figure 2. (left) $R_{AA}(p_T)$ of prompt D^0 and D^+ mesons produced in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV at mid-rapidity ($|y| < 0.5$) in the 0 – 20% centrality class; predictions with the POWLANG model are compared with ALICE data [22] on average R_{AA} of prompt D mesons versus p_T ; (right) elliptic-flow $v_2(p_T)$ of prompt D^0 and D^+ mesons at mid-rapidity ($|y| < 0.5$) in the 0 – 20% centrality class.

Our predictions for R_{AA} at low p_T are in rather good agreement with the ALICE data, within the experimental and theoretical uncertainties, while the increasing trend of R_{AA} measured at high p_T is not reproduced. In addition, POWLANG model cannot reproduce the rather high v_2 values (up to 0.15–0.2) measured by ALICE [23] at low p_T .

To conclude, we show our predictions for the measurement of semi-leptonic heavy-flavor decays in ALICE, at central rapidity. In Fig. 3 (left panel) our prediction of the differential invariant production cross section at central rapidity of electrons from heavy-flavor decays in pp collisions at $\sqrt{s}=7$ TeV is compared to ALICE data [24]. Separate contributions to electron yields from different decay channels ($D \rightarrow e$, $B \rightarrow e$ or $B \rightarrow D \rightarrow e$) are also shown. As in the case of D mesons we can conclude that, within the experimental uncertainties and the systematics affecting our calculations, our prediction for the heavy-flavor electron spectrum in pp collisions agrees reasonably with the ALICE data.

Finally, in the right panel of Fig. 3, we show our predictions for the R_{AA} of the total inclusive electron yields from heavy-flavor decays at central rapidity in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV, in three different centrality classes (0 – 10%, 10 – 20% and 30 – 50%). These predictions can be compared to the preliminary data reported by ALICE by [25], and at least qualitatively, before official data publication, we can already conclude that heavy-flavor electron R_{AA} measured by ALICE are reasonably described by POWLANG at moderate p_T .

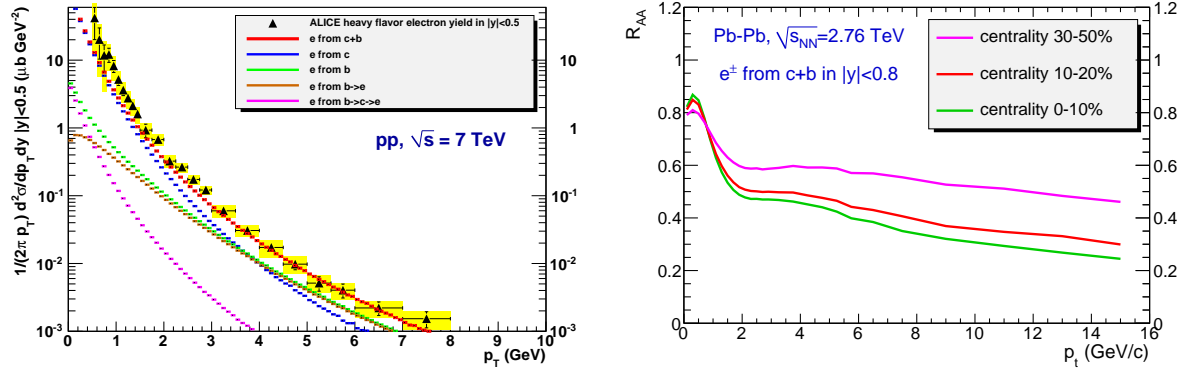


Figure 3. (left) invariant p_T -differential inclusive cross-section of electrons from heavy-flavor decays in pp collisions at $\sqrt{s} = 7$ TeV at central rapidity ($|y| < 0.5$); ALICE [24] data on the total inclusive electron yield are compared to our predictions with POWHEG+PYTHIA, including also the separate contributions to the electron yield from charm and beauty semi-leptonic decays; (right) $R_{AA}(p_T)$ of inclusive heavy-flavor electrons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at mid-rapidity ($|y| < 0.8$) and for three centrality classes: 0 – 10%, 10 – 20% and 30 – 50%.

4. Summary

The POWLANG setup provides a reasonable description of the quenching of heavy-flavor spectra measured by ALICE at the LHC in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, for moderate values of p_T . In the same p_T range the experimental results for v_2 are underpredicted. This could either point to a shortcoming of a perturbative picture of rescattering in the hot medium, or to the contribution at hadronization of coalescence, whose implementation is left for future investigations.

On the other hand at high p_T the Langevin approach seems to overestimate the observed amount of quenching.

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